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Four experiments tested a proposed extension of Double Filtering by Frequency theory by examining whether the left and right hemispheres of the human brain are differentially sensitive to high and low electromagnetic frequencies, respectively, and whether this effect is primarily based on relative or absolute frequency levels. Experiments 1 and 2 provided initial support by replicating a known hemispheric effect using different background colors. Experiments 3 and 4 provided converging evidence by varying visual field presentation and measuring participant's reaction times. These findings indicate that the right hemisphere is relatively more sensitive to low frequency colors, whereas the left hemisphere is more sensitive to high frequency ones. The findings also suggest that this difference is primarily based on absolute frequency levels. Implications and possible applications are discussed.

HEMISPHERIC DIFFERENCES IN COLOR PERCEPTION: RELATIVE VERSUS

ABSOLUTE FREQUENCY LEVELS, IMPLICATIONS

AND POSSIBLE APPLICATIONS

by

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APPROVAL PAGE

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TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

Color is ubiquitous. From the moment we wake till the time we sleep, virtually all of our thoughts, judgments and decisions are made in contexts that involve a multitude of different colors. Unfortunately, however, most of the research examining how color influences behavior has relied on correlations, post-hoc interpretations, or has proposed an account that makes predictions for the influence of one or two colors on a specific task in a specific context, offering little or no predictive value when a change is made to any of these elements (e.g., Chien, 2011; Elliot & Maier, 2007; Gerend & Sias, 2009; Levy 1984; Maier, Barchfeld, Elliot, & Pekrun, 2009; Maier, Elliot, & Lichtenfeld, 2008; Mehta & Zhu, 2009; Singh, 2006; Stone & English, 1998; Tanaka & Tokuno, 2011). Not surprisingly, a growing number of researchers have recently called for more theory and an increase in experimental rigor to provide a better explanation of these effects (e.g., Chien, 2011; Elliot & Maier, 2007; Mehta & Zhu, 2009).

One theory which I propose is relevant to this issue is Double Filtering by Frequency (DFF) theory (e.g., Ivry & Robertson, 1998) – a theory based on extensive research with both neurological patients and healthy participants that provides an explanation of hemispheric asymmetries observed in the processing of visual spatial and auditory frequencies, but not electromagnetic frequencies (i.e. colors). According to DFF theory, the left and right hemispheres of the human brain are differentially sensitive to high versus low spatial and audio frequencies, respectively, and this effect is primarily based on relative frequency levels – whether one frequency is higher or lower than other frequencies in a given context. Although DFF theory was not developed to explain how different colors influence behavior, I believe that it not only offers such an account, it also allows for a number of novel predictions and provides a well-supported, theoretical basis for a wide range of previously unrelated findings. Therefore, the purposes of this paper are twofold: (1) to examine whether DFF theory should be extended to include electromagnetic frequencies by testing for hemispheric differences in the perception of different colors and whether this difference is based on relative or absolute frequency levels; and (2) to provide a theoretically based, context independent account of how color can influence behavior and review how this can be applied to previous research in the area of color psychology. I also plan to show that this view generates a number of novel predictions that may stimulate future research.

I begin by reviewing previous work in color psychology and related areas, discussing the scant theory that has been proposed to account for the findings. Then, after describing the experience of color from a physical perspective, I review DFF theory in detail and propose an extension to include electromagnetic frequencies. Two experiments are then reported that replicated a known hemispheric effect by varying the color of the paper on which a decision-making task was presented. Experiment 3 provided converging evidence when high or low frequency stimuli (i.e. a blue or red rectangle) were presented to participants' left or right visual field and their reaction time was measured. Finally, a fourth experiment replicated the findings of Experiment 3 in an examination of whether the effect is primarily based on relative or absolute frequency levels. Thus, an initial demonstration and replication of two distinct findings supported the current view that the left and right hemispheres are differentially sensitive to high versus low electromagnetic frequencies, respectively. In the remaining sections I show that several previous findings can be reinterpreted from this view and discuss a number of implications and possible applications.

CHAPTER II

COLOR PSYCHOLOGY AND RELATED AREAS

The beginnings of color psychology can be traced back nearly to the dawn of civilization. The ancient Egyptians, for instance, are said to have used different colored lights to provide therapy for a number of different ailments (e.g., Singh, 2006). In this treatment, patients would rest under the glow of one of several different colored lights and allow their bodies to absorb its healing powers, although the precise reasoning behind this therapy is no longer clear. The ancient Greeks and Romans are also credited with using some form of light therapy. Today, however, most of the studies investigating the effects of different colors on psychological functioning do not use colored light but vary the color of one or more elements in a controlled laboratory setting. Some of these studies were conducted for marketing or organizational purposes and offer little or no theoretical explanations, whereas others offer either a relatively context independent account – one based on the physical properties of light – or a context dependent account (e.g., Singh, 2006; Stone & English, 1998; see also Elliot & Maier, 2007 and Elliot, Maier, Moller, Friedman, & Meinhardt, 2007 for review).

Consider the recent marketing article by Singh (2006). Although no studies were conducted and few were referenced, the influences that different colors have on a number of different areas were discussed with a focus on marketing application. Topic areas included the influence of color in restaurants, on waiting time, and on different brands. In each area, the influence of different colors was discussed but most often no references were provided. When references were provided they generally reported an association (i.e. correlation) between a color and some outcome (i.e. red-hunger). No explanation was offered that would allow for predictions beyond the contexts discussed or for any different colors. The author does suggest, however, a color (warm versus cool) X light (bright versus dim) "typology" for future research. In analyzing this typology, median splits are recommended to facilitate comparing means through an ANOVA – a practice that is not recommended by most statisticians (e.g., Aiken & West, 1991; Baron & Kenny, 1986).

In a study conducted for organizational purposes, Stone & English (1998) examined the influence of red or blue partitions in a workplace environment. Cubicles with either a red or blue inner panel were constructed so that participants could not see the color of any other cubical, and a scenic poster was either present or not present in the cubicle. Clerical performance – the transcription of a series of names played from a tape recorder – was measured over a series of five sessions on a low (same names) or high (different names) demand task, along with mood, perceived task demand, perceived temperature and a number of other variables. While overall performance was not affected by color and few other effects reached significance, a greater number of errors were made in session four on the low demand task in the red versus blue cubicle condition, and the temperature of the room was perceived to be lower in the blue versus red cubicle condition. This latter finding was expected based on the notion that longer wavelength colors (i.e. red and orange) tend to be experienced as warm but that shorter wavelength colors (i.e. blue and purple) tend to be experienced as cool (e.g., Whitfield & Wiltshire, 1990). The finding that more errors were made in session four on the low demand task in the red cubicle condition, however, was in reverse of that predicted; it was thought that because warm (red) versus cool (blue) colors are energizing they should facilitate performance on a monotonous task (e.g., Levy, 1984). The underlying causes of a number of other non-significant and marginal effects were also discussed as is typical with this type of research.

Goldstein (1942) is often credited with providing the theorizing from which notions such as those contained in the Stone & English (1998) article are derived (e.g., Elliot & Maier, 2007; Elliot et al., 2007). He proposed that red and yellow are stimulating, disagreeable and focus people on the outward environment, whereas green and blue are quieting, agreeable and focus people inward. These effects were thought to arise from “inherent psychological reactions” to the physical properties of light, but his position was never clearly stated and researchers have generally interpreted Goldstein’s proposal in terms of wavelength; longer wavelength colors (i.e. red and orange) are expected to produce the reactions Goldstein proposed for red and yellow, and shorter wavelength colors (i.e. blue and purple) are expected to produce the effects proposed for green and blue (see Elliot & Maier, 2007 for review).

Although proposals such as this are not specific to any one context, numerous conflicting results have been reported and they do not clearly explain how or why their effects arise (see Elliot & Maier, 2007 for review). For instance, how does wavelength cause the psychological effects associated with it? Why should different wavelengths affect individuals' outward or inward focus; does it affect the brain and if so, how? These accounts are silent on such matters. Instead, they tend to focus on the warming versus cooling or energizing versus calming properties of red and blue, respectively. In addition to these theoretical limitations there are many results that do not fit this analysis (e.g., Maier, Elliot, & Lichtenfeld, 2008; Gerend & Sias, 2009; Lindsey et al., 2010). It is also difficult to determine the effects other colors will have and it is difficult to make predictions about when the warming or energizing properties of a color are unimportant. Thus, this account is considerably limited in its ability to make predictions.

Lindsey et al. (2010) provided another context independent account – one that is based on visual search and the physical properties of light. In one study, participants searched for colored targets among desaturated distractors of the same color and white distractors. They found that search times were faster for warm colors like red and orange but slower for cool colors like blue and purple. Specifically, search times were fastest for red and more than a half second slower for the slowest color – purple. These authors attributed their finding to the early-stage linear transformations of photoreceptor signals derived from long, medium and short wave cones in the human retina. A mathematical model of this process was offered and it was shown to have good fit. However, while their model fits their data well, it is limited to accounting for performance differences in visual search and would not be able to account for color differences in any other domain. As will be discussed, this exact pattern of findings would also be expected from the current view which is able to account for a wide range of other findings.

Aside from investigations based on Goldstein's (1942) and Lindsey et al.'s (2010) proposals, most of the work on color psychology has used a context or domain specific account to explain the results (e.g., Chien, 2011; Elliot and colleagues; Gerend & Sias, 2009; Mehta & Zhu, 2009). One line of work focusing on intellectual performance is exemplified by the Maier, Elliot, & Lichtenfeld (2008) results (e.g., Elliot et al., 2007; Lichtenfeld, Maier, Elliot, & Pekrun, 2009; Maier, Elliot, & Lichtenfeld, 2008; Tanaka & Tokuno, 2011). According to their account, the color red has come to be associated with threat in school and in other performance contexts (like taking the SAT or GRE) due to years of receiving work with red corrections and red letter grades. Thus, red has a particularly salient meaning in performance contexts – threat. The presence of this red threat cue is thought to generate avoidance motivations that in turn impair intellectual performance. This account is silent, however, on the influence of all other colors in such contexts. Nevertheless, these authors found that performance on an analytic problem solving task (the 20-item numeric portion of a German IQ test) was lower when a red versus gray triangle appeared on the first page of a problem booklet. Although avoidance motivations were thought to underlie this effect, the authors were unable to observe these motivations using self-report measures and concluded that they must be unconscious.

Several issues with this view are apparent. First, it may be that red serves as a threat cue in intellectual performance contexts but it is unclear if this actually impaired performance – without knowing the effect that gray had on performance, it is unclear whether performance was actually lower in the red triangle condition or whether it increased due to gray. Similar findings were observed by the same researchers when red was varied with green but it is again unclear what effect the green color condition had on performance (e.g., Lichtenfeld et al., 2009). It may be that both gray and green cause a performance increase on intellectual performance tasks and that the performance level observed in the red color condition would have been similar to that of a control condition, but it is impossible to tell from the results. Moreover, the fact that avoidance motivations were not found when individuals completed self-report measures does not necessarily mean that they are unconscious – they may simply not exist. If this is the case, then the account given by these authors offers very little in terms of explanatory power.

A more general issue with this view, however, is that it is specific to the effects of red in intellectual performance contexts only. No account of the influence of other colors is provided and no attempt to generalize performance contexts to anything more general is made. Thus, predictions cannot be made for any other color on intellectual performance tasks, and any predictions that can be made regarding red are not generalizable to other contexts. For instance, no prediction could be made regarding the effects of red, orange, purple or blue on a visual search task but color based differences have been found (e.g., Lindsey et al., 2010).

In addition to findings in color psychology, judgment and decision making researchers have found that different colors cause various effects on individuals' choices and evaluations. For instance, Gerend & Sias (2009) varied the frame (gain or loss) of a message regarding vaccinations for the human papillomavirus (HPV) and the color of a 7 X 4 inch rectangle that appeared in two places – one on the cover of the binder containing the framed information, and one that surrounded the framed information. The rectangles were either red or gray and were not filled (i.e. they outlined the information only). In message framing studies, objectively equivalent information is presented in either positive (gains) or negative (losses) terms and the likelihood of engaging in a target behavior is measured as the dependent variable; gain framed messages describe the benefits of engaging in the target behavior whereas loss framed messages describe the costs of not engaging in the behavior. For example, a gain framed message might state “If you use sunscreen then you will be protected from the sun’s rays.” The corresponding loss framed message would then state “If you don’t use sunscreen you won’t be protected from the sun’s rays.” Typically, loss versus gain framed messages are found to be more effective (e.g., Levin, Schneider, & Gaeth, 1998; Pinon & Gambara, 2005).

In the Gerend & Sias (2009) experiment, the likelihood of obtaining the HPV vaccine served as the dependent variable and a message framing effect (loss > gain) was found when the rectangles were red but not when they were gray. This pattern was predicted based on the notion that red serves as a threat cue in health contexts, although the amount of threat perceived by participants was not measured. Nevertheless, the authors argued that health contexts are similar to performance contexts in that the color red has come to be associated with threat and may generate avoidance motivations. Several reasons were given for this, including the fact that blood is red and that it “conjures images of injury and infection”, although it is not clear why threat cues or avoidance motivations would increase message framing effects.

It is also not clear why no effect for the message frame was found when the rectangles were gray. In previous studies conducted by the same researchers, loss versus gain framed messages were found to be more persuasive even when no color manipulation was used, at least for those higher in risky sexual behavior or who had been with relatively more partners (Gerend & Shepherd, 2007; Gerend, Shepherd, & Monday, 2008). Presumably then, a similar pattern (loss > gain) should have been observed when the rectangles were gray, although the magnitude of the effect may have been larger when red rectangles were used. In this study, however, gain versus loss framed messages were rated descriptively higher when gray rectangles were used, and no analyses were reported in which risky sexual behavior or behavioral frequency were examined. Thus, it is unclear whether red enhanced what would have been a negligible message framing effect or gray diminished an otherwise larger effect.

In another investigation of the effects of color on message framing, Chien (2011) varied the red or blue background of a message promoting the H1N1 vaccination. In this study, framing effects did not differ by color condition per se, but loss framed messages were rated higher when participants were exposed to a red versus blue background. The explanation for this result was based loosely on the theorizing of Gerend & Sias (2009) in which red is thought to serve as a threat cue in health contexts, but it is not clear what effect blue had and why only loss framed messages were affected. Furthermore, from the account provided by Gerend & Sias (2009), it is unclear how other colors such as orange or purple might influence the magnitude of message framing effects or how non-health related message frames might be affected.

In sum, a considerable number of effects have been reported in which different colors had an influence on behavior, but the explanations for these effects have rarely extended beyond the specific context that was tested. There is no doubt that some colors have a specific meaning in some contexts but color may also have an influence that is independent of context. Therefore, I believe that there is a need for a well-grounded, context-independent account that describes the experience of color from a physical perspective and is able to make predictions for a wide range of colors. In the next section I begin to build the case for such an account – one that goes beyond the accounts of Goldstein (1942) and Lindsey et al. (2010).

CHAPTER III

COLOR FROM A PHYSICAL PERSPECTIVE

Physically speaking, the experience of color depends upon the dominant wavelength or frequency of the light (electromagnetic radiation) emitted from an object. The range of electromagnetic frequencies perceptible to humans is known as the "visual spectrum" and is roughly 384 Thz to 789 THz (e.g., Azeemi & Raza, 2005). One THz is equal to one trillion hertz. An object that appears blue emits (or reflects) light with a dominant electromagnetic frequency in the 631-668 THz range, whereas an object that appears red emits (or reflects) light in the 400-484 THz range. Thus, blue is a high electromagnetic frequency color and red is a low electromagnetic frequency color. Studies that have varied blue and red can, therefore, be thought of as varying the high or low electromagnetic frequencies present in the experimental context, respectively. Similarly, a study varying green and red can be seen as varying high or low electromagnetic frequencies given that green exists near the middle of the visual spectrum (526-606 THz range) and that red is relatively lower in frequency. Relevant to the current proposal, purple (668-789 THz range) is slightly higher in frequency than blue making purple a second high frequency color with blue, and orange (484-508 THz range) is slightly higher in frequency than red, but still relatively low, making orange a second low frequency color with red.

Little theory currently exists, however, to explain how differences in the electromagnetic frequencies present in a context should affect individual behavior. For instance, no context-based theory would predict that differences would be due to different electromagnetic frequencies but that red would act as a threat cue or that blue would have some other effect depending on the experimental context. In all of the studies reviewed above, only the accounts provided by Lindsey et al. (2010) and Goldstein (1942) were context independent but the former is limited to visual search and the latter was never clearly specified.

If color does have an influence that is independent of context, then context-based accounts would be silent on their effect and they would actually be confounded with them. For instance, red may serve as a threat cue and have an influence based on frequency but a context specific account that only focuses on red as a threat cue would explain the effect entirely in terms of threat. The influence based on frequency would go undetected and would be confounded with that of threat. As will be shown, this allows for a re-interpretation of the results of a number of prior studies in terms of electromagnetic frequency.

CHAPTER IV

DOUBLE FILTERING BY FREQUENCY THEORY

Overview

Double Filtering by Frequency (DFF) theory is based on years of research with both neurological patients and healthy participants, and provides an explanation of hemispheric asymmetries observed in the processing of spatial frequencies and audio frequencies (e.g., Christman, Kitterle, & Hellige, 1991; Christman, Kitterle, & Niebauer, 1997; Flevaris, Bentin, & Robertson, 2011; Ivry & Lebby, 1993; Kitterle, Christman, & Hellige, 1990; Kitterle, Hellige, & Christman, 1992; List & Justus, 2007; Robertson, 1996; Robertson & Ivry, 2000; Sergent, 1982). Spatial frequency refers to the proportion of visual field occupied by an object and audio frequency is a function of pressure variations that propagate through the air. Experiments that have investigated spatial frequency asymmetries have most often presented participants with either sinusoidal gratings or hierarchically structured (i.e. Navon) letters (e.g., Christman, Kitterle, & Hellige, 1991; Christman, Kitterle, & Niebauer, 1997; Robertson, 1996; Sergent, 1982). Sinusoidal gratings are composed of alternating light and dark shaded bars and the greater the number of alternating areas the greater the spatial frequency of the stimulus. Hierarchically structured letters, on the other hand, are generated by forming a relatively large letter out of smaller ones. Because the larger letter occupies a greater amount of visual angle than the letters that form it, the larger letter is the low frequency (global) component of a hierarchical stimulus and the smaller letters that make it up are the high frequency (local) component. Audio frequencies, meanwhile, are experienced as high or low pitch tones; higher pitch tones are caused by relatively high audio frequencies and lower pitch tones are caused by relatively low audio frequencies (e.g., Ivry & Lebby, 1993; List & Justus, 2007; Robertson & Ivry, 2000).

According to DFF theory, the left and right hemispheres of the human brain are relatively more sensitive to the high and low spatial (and audio) frequencies present in a given context, respectively. This difference in sensitivity results in a performance advantage for the left hemisphere in processing high frequency information and an advantage for the right hemisphere in processing low frequency information. Importantly, these asymmetries are thought to be the result of a two stage process called "double filtering". In the first stage of filtering, an attentional mechanism selects a "relevant range" of frequencies from the full range of frequencies initially presented to each hemisphere – those that are necessary for the processing of the stimulus. This relevant range is further operated on in the second stage of filtering. In this stage, the left hemisphere amplifies the relatively high frequencies (audio or spatial) in the relevant range, whereas, the right hemisphere amplifies the relatively low frequencies. Thus, the second stage of filtering produces the asymmetric representation of information responsible for performance differences between the hemispheres.

One of the first demonstrations of this asymmetry was provided by Sergent (1982) who presented hierarchically structured letters to the left visual field/right hemisphere (LVF/RH) or right visual field/left hemisphere (RVF/LH) of healthy participants and measured their reaction time in identifying the low or high frequency component of the stimulus. Consistent with DFF theory, a RVF(LH) advantage was found for the high frequency (local) component but a LVF(RH) advantage was found for the low frequency (global) component. That is, reaction times were lower for low versus high frequency stimuli when presented to the right hemisphere but they were lower for high versus low frequency stimuli when presented to the left hemisphere – a frequency X hemisphere interaction was found.

A more dramatic demonstration of this global-local asymmetry, however, can be found with neurological patients with recent stroke damage (e.g., Ivry & Robertson, 1998). In a host of studies reviewed by Ivry & Robertson (1998) stroke patients with recent unilateral damage to either their left or right hemisphere were asked to recreate a hierarchically structured stimulus that was presented to them. Although all were able to see the stimulus normally, those with damage to the left hemisphere were virtually unable to recreate the local component and instead tended to draw a simplified version of the global component. For example, if the global component was an M and Z was the local component, a patient with left hemisphere damage would simply draw a large M. Those with right hemisphere damage, on the other hand, were able to recreate the local component but arranged these letters either in a form that was not related to the global component or in a random fashion. While these effects became less dramatic over time, they provide strong evidence that the left and right hemispheres differentially process high and low spatial frequencies.

A similar pattern has been found in individual's response to auditory frequencies. To test whether hemispheric differences in audio perception are similar to those in vision, Ivry & Lebby (1993) presented participants with sets of either high or low frequency tones in the left ear (RH) or right ear (LH) and measured their reaction time in identifying relatively high or low frequency tones in the set. Although no specific parallels between auditory and visual perception were discussed, as with spatial frequencies, a performance advantage was found for relatively low frequency tones when presented to the left ear (RH) but an advantage for relatively high frequency tones was found when presented to the right ear (LH). This finding has been supported in numerous subsequent investigations with auditory stimuli (e.g., Gallagher & Dagenbach, 2007; List & Justus, 2007; McCormick & Seta, 2011; Robertson & Ivry, 2000; Seta, McCormick, Gallagher, McElroy, & Seta, 2010). Thus, evidence supporting a DFF based account of hemispheric asymmetries has been found previously for both spatial and auditory frequencies.

DFF Data Analysis

Two types of findings obtained in this work have been reported. In one, average (or median) response times have revealed that respondents were faster to identify low frequency stimuli when presented in their LVF/RH versus RVF/LH. In contrast, respondents were faster to identify high frequency stimuli when presented to their RVF/LH versus LVF/RH (e.g., Christman, Kitterle, & Hellige, 1991; Christman, Kitterle, & Niebauer, 1997). This is the most commonly reported finding in DFF based research (e.g., Ivry & Robertson, 1998). If similar findings apply to electromagnetic frequencies, then faster reaction times should be found for a low frequency color (i.e. red) when presented to participants' left versus right visual field and faster reaction times should be found for a high frequency color (i.e. blue) when presented to their right versus left visual field.

A second finding that also supports DFF theory involves "level specific" priming in which participants' response times are faster on the second versus first trial when the same level of a stimulus (high or low frequency) is presented on consecutive trials (e.g., List & Justus, 2007; Robertson, 1996). Robertson (1996), for example, presented hierarchical stimuli to either the LVF/RH or RVF/LH and measured participants' reaction time in identifying the stimuli at the global or local level. Level specific priming was found for both global and local stimuli; participants' response times were faster when the same level (global/low or local/high) was presented on consecutive trials than when the level changed. The author proposed that this was due to an "attentional print" in which attention to a global or local level on a preceding trial guides parsing of the visual field on a subsequent trial. In a second study, the attentional print was shown to last for at least three seconds and level specific priming was found regardless of whether the location (hemisphere) changed or stayed the same.

Later research with audio based stimuli, however, found that level specific priming for this type of frequency does depend on the location: whether location changes or stays the same (e.g., List & Justus, 2007). In this work, priming effects were greater when there was a match (i.e. low frequency-right hemisphere and high frequency-left hemisphere) between audio frequency and hemisphere than when there was a mismatch (i.e. low-left and high-right). Participants were about 110ms faster on the second trial when there was a match between target level and location but this was reduced to 80ms or less when there was a mismatch. This pattern produced a significant frequency X hemisphere interaction. Thus, asymmetric priming for low and high frequencies inline with DFF theory predictions has been found for both spatial and audio based stimuli, and for audio stimuli, this pattern depended on whether there was a match or a mismatch between frequency and hemisphere.

As it applies to electromagnetic frequencies, level specific priming would refer to priming for specific colors – low electromagnetic frequencies are exemplified by red and high electromagnetic frequencies are exemplified by blue. Therefore, a low electromagnetic frequency priming effect would occur if red was presented on consecutive trials and participants responded faster on the second trial. A high electromagnetic frequency priming effect, on the other hand, would be found if blue was presented on consecutive trials and participants responded faster on the second. Given, however, that no theory currently proposes hemispheric differences due to different electromagnetic frequencies, the null hypothesis would either be that no priming effect should be found or that priming should not differ between colors or between hemispheres.

DFF's Neurological Basis

Although DFF theory has been supported in numerous behavioral investigations, relatively little is known about its neurological underpinnings. According to the authors of DFF theory, identical information is presented to each hemisphere initially and the performance asymmetries that are observed between hemispheres arise beyond the sensory processing stage when individuals make judgments or decisions (e.g., Ivry & Robertson, 1998). In other words, laterality effects are proposed to be the result of "higher-order filtering processes superimposed on sensory representations" (e.g., Ivry & Robertson, 1998, pp. 105). This central tenet of DFF theory is important in that it accounts for at least two notable findings that may offer some insight into the origin of these asymmetries.

First, identification but not detection tasks have consistently revealed performance differences between the hemispheres inline with DFF theory predictions (e.g., Christman, Kitterle, & Hellige, 1991; Kitterle, Christman & Hellige, 1990; List & Justus, 2007; Robertson, 1996; Robertson & Ivry, 2000). Identification tasks require participants to form a judgment about a stimulus ("thin" or "wide" bars, or "high" or "low" tone) whereas detection tasks require only that the presence or absence of a stimulus is detected. Both tasks involve sensory level processing but only identification tasks involve higher-order processing. Thus, if sensory processing mechanisms were primarily responsible for the asymmetries found in identification tasks, then a similar pattern should have been found in detection tasks. Given that this was not the case, sensory mechanisms do not seem to underlie performance differences between the hemispheres and, perhaps, only post-sensory mechanisms should be considered as possible candidates for producing DFF consistent effects. Further work has supported this notion in that a difference in event-related potentials (ERP's) was found after the sensory processing stage when individuals identified global or local stimuli, but no difference was found prior to that at the sensory processing stage (e.g., Heinze & Munte, 1993).

If sensory mechanisms are not the primary means by which DFF consistent effects arise then we can eliminate a considerable portion of the visual physiology of the brain from consideration. While this is tempting, several findings in the detection literature warrant review. For instance, detection research has found that there are three primary "retino-cortical" pathways that carry different visual information from sensory cells in the retina (i.e. rods and cones) to the primary visual cortex – the magnocellualar (MC), parvocellular (PC) and koniocellular (KC) pathways (e.g., Lee, Sun, & Valberg, 2011; Ribeiro & Castelo-Branco, 2010; West, Anderson, Bedwell, & Pratt, 2010). The phylogenetically older MC pathway is tuned to low spatial frequencies, has been characterized as the "where" pathway, and transfers achromatic information from retinal rods (e.g., Ribeiro & Castelo-Branco, 2010; West et al., 2010). The PC pathway on the other hand is phylogenetically newer, tuned to higher spatial frequencies, has been characterized as the "what" pathway, and carries long-medium cone (i.e. red-green) contrast information (e.g., Ribeiro & Castelo-Branco, 2010; West et al., 2010). Finally, although less is known about the KC pathway, it is sensitive to short cone (i.e. blue-yellow) contrast and thus plays a role in color vision (e.g., Ribeiro & Castelo-Branco, 2010).

These findings are intriguing in that they appear, at least on the surface, to relate to the current discussion, particularly to spatial frequency lateralization effects. If the MC pathway, that is tuned to low spatial frequencies, projects information primarily to the right hemisphere – as suggested by some researchers (e.g., Kosslyn, Chabris, Marsolek, & Koenig, 1992; Howard & Reggia, 2007) – and the PC pathway, that is tuned to high spatial frequencies, projects information primarily to the left hemisphere, then a straightforward explanation of the underlying physiology of (some) DFF consistent effects would be apparent – lateralization effects would be driven by the relative contributions of the magnocellular and parvocellular pathways to right versus left hemisphere processing, respectively. Unfortunately, however, these pathways operate automatically at the sensory level and any contribution they may have in producing DFF consistent effects should be found in both identification and detection tasks. Given that this is not the case, it is unclear how the MC and PC pathways could be the primary structures underlying spatial frequency effects, much less those of audio or, as will be proposed, electromagnetic frequencies.

Furthermore, such an account would seem to result in absolute differences in frequency sensitivity between the hemispheres. This prediction, however, is inconsistent with the finding that hemispheric asymmetries appear to operate on a relative, in addition to absolute, frequency basis. Specifically, the same stimulus (e.g., a 2cpd grating) has been found to be processed differently by the two hemispheres depending on whether it was relatively higher or lower in frequency than other stimuli in the same context (e.g., Christman et al., 1991). In this work, a 2cpd sinusoid grating was presented in a context with lower frequency stimuli (.5cpd and 1cpd) or higher frequency stimuli (4cpd and 8cpd) to create relatively high and low frequency conditions, respectively. Low frequency (.5cpd and 1cpd) and high frequency (4cpd and 8cpd) baseline conditions were also used. For each of two blocks of trials, participants were shown examples of the baseline two-component stimulus (i.e. .5cpd and 1cpd or 4cpd and 8cpd) and they were instructed to identify whether the 2cpd component was either present or not present. The location of the 2cpd component was alternated so that participants could not simply detect its presence.

A significant LVF/RH advantage in response time was observed in the low frequency baseline condition but this was eliminated when the 2cpd stimulus was added to the low frequency context. Thus, the 2cpd stimulus increased the role of LH processing when it was relatively high in frequency. The same 2cpd stimulus had a different effect, however, when it was added to the high frequency baseline condition; a descriptive RVF/LH advantage found in the baseline condition was reversed by the 2cpd stimulus and a LVF/RH advantage was found. Similar findings have also been reported with audio stimuli (e.g., Gallagher & Dagenbach, 2007; Robertson & Ivry, 2000; Seta et al., 2010). Thus, hemispheric asymmetries for both spatial and audio frequencies appear to operate on a relative – as well as absolute – frequency basis.

While this finding does not necessarily preclude any additional brain regions from consideration, it does pose an additional challenge for biologically based accounts that often propose hard-wired differences in filter size or in the distribution of these filters between hemispheres or in the number of connections to cortical areas (e.g., Hellige, 1993; Howard & Reggia, 2007; Kosslyn et al., 1992). Such accounts imply an absolute difference in hemispheric sensitivity and have difficulty explaining relative frequency differences. One biologically based account that sought to address at least some of these issues was, nevertheless, recently proposed by Howard & Reggia (2007).

Based on Hellige's (1993) proposal, Howard & Reggia (2007) argued that the PC pathway matures later in time than the MC pathway and that this coincides with an increasing sensitivity to higher spatial frequencies; this developmental process results in a RH bias toward low spatial frequencies and a LH bias toward high spatial frequencies. Further, the connections of cells in the visual cortex (i.e. V1 to V2 connections) are said to be modified during postnatal development as responsiveness to high spatial frequencies continues to increase, and this contributes to the lateralization of spatial frequencies. Thus, hard-wired asymmetries in conjunction with an earlier developing right versus left hemisphere were said to underlie spatial frequency lateralization effects.

A simulation study conducted by these authors supported their theory when right versus left hemisphere processing was assumed to begin before the other. An attempt was also made to account for the existence of relative frequency effects, although this was not tested in their simulation. Specifically, it was hypothesized that the presentation of either low (i.e. .5cpd and 1cpd) or high (i.e. 4cpd and 8cpd) spatial frequency stimuli not only activates filters at these frequency levels but also increases the activation of neighboring filters (i.e. 2cpd). Thus, if a 2cpd stimulus is added to a context containing a .5cpd and a 1cpd stimulus, the 2cpd filter would be activated but, more saliently, the 4cpd filter which neighbors the 2cpd filter would now become partially active. If a 2cpd stimulus were added to a high frequency context containing a 4cpd and an 8cpd stimulus, however, the 2cpd filter would become active but, more saliently, the neighboring 1cpd filter would also become partially active. If this reasoning is correct and 4cpd stimuli are preferentially hard-wired to the left hemisphere while 1cpd stimuli are hard-wired to the right hemisphere, then an alternative, biologically based, explanation may be provided for the Christman et al. (1991) finding of relative spatial frequency effects.

Unfortunately, however, this account fails to explain other relative frequency findings (e.g., Hellige, 1993) and, because the PC and MC pathways would underlie these effects, similar findings should be observed whether the task requires identification or detection of the stimuli. As reviewed earlier, DFF consistent effects arise only for identification behaviors. Howard & Reggia (2007) failed to reference this limitation in their article and make no provision for it in their theory, leaving important questions unanswered in their account of spatial frequency lateralization effects. Furthermore, this theory is silent on audio frequency lateralization effects and would make no predictions regarding electromagnetic frequencies. Therefore, its usefulness in explaining the full range of prior DFF consistent findings or those proposed in this paper is questionable.

So what does underlie DFF theory? At least for spatial frequencies, one important brain region may have been identified – the temporal-parietal junction. Ivry & Robertson (1998) reviewed a series of studies that found some role for the temporal-parietal junction while ruling out other areas. In one set of studies, recent stroke patients were selected on the basis of whether their lesions (i.e. brain damage) were in the left or right temporal-parietal junction (and surrounding extrastriate areas), or whether their lesions were located elsewhere. Hierarchical letters were presented centrally and participant's reaction time in identifying global or local stimuli was measured. Performance was lower for left temporal-parietal damaged participants when identifying local shapes but lower for right temporal-parietal damaged participants when identifying global shapes. Conversely, performance did not differ between global and local identification for patients whose cortical damage occurred outside of the temporal-parietal junction. Thus, at least for spatial frequencies, the operation of the temporal-parietal junction seems to be necessary for global/local asymmetries to arise (e.g., Ivry & Robertson, 1998).

How or why this area becomes active when such judgments are necessary is unclear but the right and left temporal-parietal junctions have been found to be important in the formation of empathy, theory of mind, in representing others' beliefs and other high-order processes (e.g., Decety & Lamm, 2004; Samson, Apperly, Chiavarino, & Humphreys, 2004). These findings are inline with the notion that DFF consistent effects are the result of higher-order processing and not low-level sensory processing. Whether or not the temporal-parietal junction is sufficient in producing these effects, however, or whether other structures are necessary will have to await future research.

Even less is known about the underlying neurology of audio frequency lateralization effects. Given that audio frequency effects are thought to arise beyond the sensory processing stage and have been shown to operate on a relative frequency basis (e.g., Ivry & Lebby, 1993; Gallagher & Dagenbach, 2007; List & Justus, 2007; Seta et al., 2010), the temporal-parietal junction would seem likely to be important for audio frequencies as well. The authors of DFF theory, however, suggest that the neural mechanisms of each modality are most likely separable (e.g., Ivry & Robertson, 1998). In a study with lobectomy patients, typical DFF effects were found (i.e. faster high frequency-LH performance and faster low frequency-RH performance) but the area of damage was largely anterior to the temporal-parietal junction and this area was considered unlikely to be involved. This finding, along with the observation that the correlation between visual and auditory lateralization measures is typically low (e.g., Hellige, 1993), led the authors to propose the existence of "modality-specific mechanisms" for audio and visual lateralization effects but they were unable to name a specific area for audio frequencies.

In regard to electromagnetic frequencies, any effects consistent with DFF theory would be expected to arise beyond the sensory processing stage and to operate on a relative frequency basis. Thus, although the parvocellular and koniocellular pathways transfer information about relatively low and high frequency chromatic information, respectively, I would not expect them to be responsible for producing any observed lateralization effects. Instead, the temporal-parietal junction would be considered as an initial candidate because it has been implicated as an important area in the processing of other visual information (i.e. spatial frequencies).

Summary

DFF theory seeks to provide an explanation for both spatial and audio frequency lateralization effects but not electromagnetic ones. This theory proposes that through a two-stage process known as "double filtering" the left hemisphere preferentially processes high frequency information whereas the right hemisphere preferentially processes low frequency information. Effects consistent with DFF theory have been observed in numerous tests with both healthy participants and neurological patients and the results of such tests typically find either performance differences between the hemispheres in terms of mean (or median) reaction times or in the magnitude of level specific priming.

Although the underlying neurology of DFF theory is unclear, some progress has been made in narrowing down the field of candidate areas. First, sensory mechanisms do not seem to provide an adequate explanation for either relative frequency effects or the finding that identification but not detection tasks produce DFF consistent effects. Therefore, these processes can likely be eliminated as being primarily responsible for lateralization effects and post-sensory areas such as the temporal-parietal junction can be considered. The temporal-parietal junction appears to play a critical role in global/local judgments in spatial frequency tasks but a somewhat more anterior area is likely to be responsible for audio frequency effects (e.g., Ivry & Robertson, 1998). DFF theory has not been investigated in regard to electromagnetic frequencies but given that this type of frequency exists in the visual modality and that the underlying neural mechanisms have been proposed to be modality specific, the temporal-parietal junction would seem to be an initial area of interest. Future work will be needed, however, to fully explain the processes by which any of these effects arise.

CHAPTER V

PROPOSED EXTENSION

Despite the fact that color is a ubiquitous feature of most contexts and that different colors have been shown to have numerous effects on behavior, relatively few theories have been proposed to explain these effects. As previously discussed, most of the theories that have been proposed are context specific and are able to make predictions only for the few colors that have been tested in that context. While some colors certainly have a specific meaning in some contexts, I believe that color may also have an influence that is independent of context. Two context independent accounts have been proposed but Goldstein's (1942) was never clearly articulated and Lindsey et al.'s (2010) is considerably limited in its scope. As a result, there is a need for a well-grounded, context independent theory that is able to make predictions for a wide range of colors. I propose that an extension of DFF theory would not only provide such an account but would also allow for a number of novel predictions and provide a well-supported, theoretical basis for a host of previously unrelated findings. Currently, however, DFF theory applies only to spatial and audio frequency effects, and not to those arising from different electromagnetic frequencies (i.e. colors). Therefore, I propose to extend DFF theory to include the effects of different electromagnetic frequencies on individual behavior.

There are a number of similarities between electromagnetic and audio frequencies that lead me to suggest that an extension of DFF theory to include electromagnetic frequencies is physically possible – both types of frequencies propagate through the environment in a similar manner (waves/frequencies) and the relevant human physiologies (long, medium and short wave cones in the visual system, and the tympanic membrane in the audio system) are both sensitive to frequency information. In addition, there seems to be less of a difference between spatial and electromagnetic frequencies than between spatial and audio frequencies, but DFF theory was previously extended to the latter.

That is, originally, DFF theory sought to explain spatial frequency effects only but it was later extended to include audio frequencies (e.g., Ivry & Robertson, 1998). Thus, the effect of one type of frequency based visual information (i.e. spatial frequency) was already explained by DFF theory, and this theory was successfully extended to include a type of frequency which is arguably quite different (i.e. audio frequency). Both spatial and electromagnetic frequencies are initially detected by the eye and are passed to the visual cortex along one (or more) of the three primary visual pathways (i.e. the magnocellular, the parvocellular and the koniocellular). Audio frequencies, however, are initially detected by the ear and are passed to audio centers of the brain along pathways that are distinct from visual ones. In comparison then, an extension of DFF theory to include electromagnetic frequencies is a relatively modest step.

A considerable amount of empirical evidence has, nevertheless, supported a DFF based account of both spatial and audio frequency effects. Research with both healthy subjects and neurological patients, with identification versus detection tasks, and with different types of audio and visual stimuli have all found a similar pattern – greater RH performance in identifying low frequency stimuli and greater LH performance in identifying high frequency stimuli. Thus, it seems clear that the hemispheres differ in their processing of both spatial and audio frequencies. If these effects can be accounted for by a single theory even though the type of frequency and the physiology by which they are processed are different, then at least from a sensory level perspective, there does not appear to be any reason why such an account cannot hold for electromagnetic frequencies.

If this extension is correct, then the context independent influence of different electromagnetic frequencies on behavior occurs through a two stage filtering process. This process begins when an individual forms a judgment or makes a decision about an object or stimulus that they are visually attending to. In the first stage of filtering, the electromagnetic frequencies (i.e. colors) that exist in the attended area (i.e. the object or stimulus) become the relevant range of frequencies. At this point, the information presented to each hemisphere is identical. In the second stage of filtering, however, the left hemisphere amplifies the relatively high electromagnetic frequencies in the relevant range whereas the right hemisphere amplifies the relatively low frequencies. This differential amplification results in the asymmetrical representation of information that gives rise to electromagnetic frequency lateralization effects. If the judgment or decision primarily involves low frequency information then RH processing should be dominant; if the task primarily involves high frequency information then LH processing should be dominant. This single account allows for the reinterpretation of several previous findings and affords a number of novel predictions.

CHAPTER VI

OVERVIEW OF EXPERIMENTS

If the current view is correct and the left and right hemispheres are differentially sensitive to high versus low electromagnetic frequencies, then we should find differences in behavior consistent with prior lateralization research when high versus low frequency colors are present in a given context. In the following chapters, four experiments are reported that test this prediction and provide support for the current view. In Experiment 1, an attribute framing task was presented on colored paper and, consistent with previous research, a framing effect was found when RH processing was enhanced by a red or orange background but not when LH processing was enhanced by a blue or purple background. Experiment 2 tested an alternative interpretation of these results and replicated the finding using a different attribute framing task. Then, following a pilot study, further evidence for the current view was found in Experiment 3 when we presented high or low frequency stimuli (i.e. a blue or red rectangle) to participant's left or right visual field and measured their reaction times. Finally, Experiment 4 provided a logical replication of Experiment 3 in a test of whether the current finding is primarily based on relative versus absolute frequency differences. Together, these studies provide an initial demonstration and replication of two distinct effects that offer converging evidence for the current view. Several reinterpretations, implications and possible applications are discussed after data presentation.

CHAPTER VII

EXPERIMENT 1

Our first prediction is based on the finding that with auditory stimuli, amplification of the high or low auditory frequencies in a message alters the extent of left or right hemispheric processing, respectively (e.g., McCormick & Seta, 2011). Applied to electromagnetic frequencies, low frequency amplification would result in the reddening/orange-ing of a stimulus or context, whereas, high frequency amplification would result in a bluer/more purple context. Therefore, given a manipulation that is typically presented on white paper, one way to increase (or amplify) the amount of low electromagnetic frequencies in the context would be to present the stimulus on red or orange paper – on a red or orange background. Alternatively, the high electromagnetic frequencies could be increased by presenting the stimulus on blue or purple paper. From our perspective then, red and orange are expected to have a similar effect and result in enhanced right hemisphere processing, whereas, blue and purple are expected to enhance left hemisphere processing.

This most basic prediction was first tested in Experiment 1. In this experiment, we sought to replicate earlier work in which an attribute framing effect (more positive ratings when the target is framed in a positive versus negative manner) was found when right but not left hemisphere processing was enhanced (e.g., McCormick & Seta, 2011; Seta, et al., 2010). Accordingly, we used an attribute framing manipulation and predicted a color frequency (high or low) X frame interaction in which a framing effect would be found when right hemisphere processing was enhanced by red or orange paper (i.e. low frequency colors), but that a relatively weak effect would be found when left hemisphere processing was enhanced by blue or purple paper (i.e. high frequency colors).

Method (Experiment 1)

Participants, Design and Procedure

Fifty-three participants (37 women) were randomly assigned to conditions. Two were excluded, however, because our exit questionnaire revealed that they did not eat beef – the target of our message. Data was collected in a single session in a large classroom. We varied the frame (positive or negative) and the color of the paper on which the information was presented (blue, red, purple or orange) in a 2 X 4 between-subjects design.

Each participant was given a vignette that contained instructions and the framing manipulation. The instructions were similar to those used in previous research (e.g., Levin, 1987; Seta et al., 2010); participants were told that, because we were interested in the associations or thoughts that come to mind when making consumer purchases, they would be asked to indicate which item in a pair of possible associates (i.e., good tasting or bad tasting) they were most likely to associate with the purchase of ground beef that was 85% lean or 15% fat. “85% lean” served as the product description in the positive condition, whereas “15% fat” was used in the negative condition. All other aspects of the message were identical and this information appeared on a piece of paper that was blue, red, purple or orange.

After reading the message – framed in positive or negative terms – participants rated the product (i.e. ground beef) on two dimensions: greasy/greaseless, and fat/lean. Each rating was given on a different 10 point scale in the order listed, with the first item in each pair anchored to the "1" and the second item anchored to the "10". Participants were asked to "Place an X anywhere on the scale that best represents your feeling." Finally, to ensure that the message was similarly easy to read in the different color conditions, participants were asked "How difficult was it to read the questionnaire?" (1 = very easy, 10 = very difficult).

Results and Discussion (Experiment 1)

An ANOVA conducted on the ease of reading item with Paper Color (blue, red, purple or orange) entered as a between-subjects factor confirmed that the message was easy to read across color conditions (*M's* = 1.86-2.93; $F < 1$). Moreover, no difference in framing was found between the red and orange or the blue and purple conditions (*F's* < 1), and the data were collapsed into respective low and high frequency groups. A 2 X 2 ANOVA on the combined fat/lean and greasy/greaseless product ratings ($r = .46$, $p < .001$) with Frame (positive or negative) and Frequency level (high or low) entered as between subjects factors revealed a main effect for the attribute frame qualified by a frame X frequency level interaction, $F(1, 47) = 4.08$, $p < .05$ and $F(1, 47) = 5.08$, $p < .03$, respectively (see Appendix A for means). We performed planned contrasts to decompose this interaction. Framing effects were pronounced when right hemisphere processing was enhanced, as was the case when the message was delivered with a low frequency background color (i.e. red or orange), $t(22) = 2.79$, $p < .02$, $d = 1.13$. When left hemisphere processing was enhanced by the presence of a high frequency background color (i.e. blue or purple), however, framing effects were not obtained, $F < 1$.

Although these results provide only indirect support, they are consistent with our account and would be difficult to explain based on any proposed contextual meaning for a given color. That is, any meaning proposed for red would have to be extended to include orange (or vice versa) and any meaning proposed for blue would have to be extended to include purple. Thus, these results provide support for an extension of DFF theory to include electromagnetic frequencies.

CHAPTER VIII

EXPERIMENT 2

One possible alternative account of Experiment 1 involves a "match" hypothesis; given that the target product used in this study (i.e. ground beef) is typically red when it is purchased in the store, it is possible that the results were driven at least partially by a match between red (and to a lesser extent orange) and ground beef versus a mismatch between this product and either blue or purple. A match may increase the strength of framing effects because it increases the strength of the frame-product association. To test whether the match hypothesis or the current view more accurately accounts for the results of Experiment 1 a bottled water product was framed in Experiment 2; pre-testing showed this product to be associated with blue and not red or orange. If the match hypothesis is correct then attribute framing effects should be greater when the background color is blue (and to a lesser extent purple) than when it is red or orange. Conversely, if the current account is correct and low frequency colors activate the right hemisphere whereas high frequency colors activate the left hemisphere, the same pattern of results that was found in the first study should be found in Experiment 2 – framing effects should be greater when a red or orange versus a blue or purple background is used. A greater number of individuals also took part in Experiment 2 to increase the reliability of our results.

Method (Experiment 2)

Participants, Design and Procedure

One-hundred and sixteen participants (78 women) were randomly assigned to conditions. Three were excluded because they indicated that they had completed the same vignette previously, and four others were removed as the result of an outlier analysis (studentized residuals > 2.6 for each). The procedure for Experiment 2 was identical to Experiment 1 except that a bottled water product was framed instead of ground beef. In the positive framing condition "99% pure" served as the product description; "1% impure" was used in the negative framing condition. Participants rated the bottled water product on three separate dimensions: impure/pure, would not buy/would buy, and would not drink/would drink. Each rating was given on a different 10 point scale as in Experiment 1.

Results and Discussion (Experiment 2)

An ANOVA conducted on the ease of reading item showed that this rating differed between color conditions (*M's* = 2.19-3.64), $F(3,103) = 3.73$, $p < .02$. Importantly, however, the ease with which the information was read does not seem to have influenced the magnitude of framing effects – no framing effect was found for the easiest (blue) or most difficult (purple) to read colors, but a significant effect was found at intermediate ease of reading levels (red and orange). Thus, we do not believe that ease of reading had a meaningful influence on our results.

Initial analyses of the dependent variables in this study revealed a similar pattern for the first two measures (impure/pure, and would not buy/would buy; $r = .69$, $p < .001$)

but a different pattern for the third (would not drink/would drink). Specifically, a framing effect was found (at least descriptively) for the third measure regardless of color condition. Given this finding, we combined only the first two measures (participant's purity and willingness to buy responses) in our primary analysis.

No difference was found between the red and orange or the blue and purple conditions (*F's* < 1), and, therefore, the data were collapsed into respective low and high frequency groups. A 2 X 2 ANOVA with Frame (positive or negative) and Frequency level (high or low) entered as between subjects factors found main effects for the attribute frame and frequency level that were qualified by an interaction between frame and frequency level, $F(1, 105) = 6.61$, $p < .02$, $F(1, 105) = 8.44$, $p < .01$ and $F(1, 105) = 4.32$, $p < .04$, respectively (see Appendix B for means). Planned contrasts revealed that framing effects were pronounced when right hemisphere processing was enhanced, as was the case when the message was delivered with a low frequency background color (i.e. red or orange), $t(51) = 3.02$, $p < .01$, d =.82. Conversely, no effect was found when left hemisphere processing was enhanced by the presence of a high frequency background color (i.e. blue or purple), $F < 1$.

These findings replicate those of Experiment 1 and provide additional support for the notion that low electromagnetic frequency colors (i.e. red and orange) preferentially activate right hemisphere processing, whereas high electromagnetic frequency colors (i.e. blue and purple) preferentially activate the left hemisphere. Across two experiments, we found that orange paper produced similar effects to red and that purple paper produced similar effects to blue, at least for attribute framing. The consistency of these results also argues strongly against a “match hypothesis” in which framing effects are expected to increase when there is a match between a product and the color it is presented with.

CHAPTER IX

EXPERIMENT 3

Although the results of Experiments 1 and 2 supported the current view, more direct evidence could be obtained using an identification task in which stimuli are presented to the LVF/RH or RVF/LH and participants' reaction times are measured. As reviewed in Chapter IV, this paradigm has been used in numerous tests of DFF theory for both visual spatial and auditory frequency lateralization effects and findings have typically been reported in terms of either mean (or median) reaction times or level-specific priming (e.g., Christman, Kitterle, & Hellige, 1991; Christman, Kitterle, & Niebauer, 1997; Flevaris, Bentin, & Robertson, 2011; Ivry & Lebby, 1993; Kitterle, Hellige, & Christman, 1992; List & Justus, 2007; Robertson, 1996; Robertson & Ivry, 2000).

Based on the results of a pilot study we expected to find results similar to those of List & Justus (2007) in that the magnitude of priming effects would depend on location (i.e. match versus mismatch) and result in a Hemisphere X Color frequency interaction. In this pilot study, a red or blue rectangle was presented randomly to participant's left or right visual field and their reaction time was measured. Analyses of mean (and median) response times failed to produce any reliable pattern of results but differences in priming effects were found; consistent with the current view, a cross-over interaction was observed in which priming effects for blue were greater in the RVF/LH versus LVF/RH but the reverse was true for red, $F(1,3) = 21.85$, $p < .02$.[1] In this study (and in Experiment 3), however, only one level of a stimulus (i.e. high or low) was presented on a given trial and the results were more akin to identity (or repetition) priming than level-specific priming. Nevertheless, such findings demonstrate that the hemispheres differ in their sensitivity to high or low frequency colors. Accordingly, a counterbalanced stimulus file was used in Experiment 3 instead of random presentation to specifically test for priming effects.

Method (Experiment 3)

Participants, Design and Procedure

Thirty right-handed female undergraduates participated in Experiment 3; only right-handed females were recruited to be consistent with previous research and increase the homogeneity of the sample. Each reported normal or corrected to normal vision and had no difficulty completing the color identification task. Stimuli consisted of a blue or red rectangle 2” wide X 4” tall that was completely filled in and created using image editing software. The blue stimulus had RGB values of 0,0,196, the red stimulus had RGB values of 196,0,0 and luminance was balanced across colors.

Data was collected from each participant individually and handedness was assessed prior to each session using the Edinburgh handedness inventory (e.g., Oldfield, 1971); a score of 40 or greater indicated right handedness. Then participants were light adapted for 2min in an otherwise darkened room, seated 54cm from a computer screen and asked to place their head in a headrest to reduce any motion. Instructions were read during this time and the need for participants to be as fast and accurate as possible was stressed. Then participants completed two blocks of 128 trials in which a stimulus (i.e. a colored rectangle) was presented 4° to the left or right of a fixation point and the participant's task was to identify whether it was a target stimulus or a distractor stimulus – when red was the target color, blue served as the distractor stimulus; when blue was the target, red was the distractor. The side of stimulus presentation was determined by a counterbalanced stimulus file that ensured an equal number of critical trials were presented in each condition (described below).

At the beginning of each trial, a central fixation consisting of a white plus sign was presented over a black background for 500ms followed by the stimulus presentation for 150ms. A mask was then presented until participants responded and a 1s inter-trial interval separated each trial. Participants used the index finger of one hand to identify target stimuli and the index finger of their other hand to identify distractor stimuli. The order in which the blocks were presented and the hand of response were counterbalanced across subjects. A 20-trial practice block was completed prior to each experimental block and breaks were offered as needed.

CounterBalanced Stimulus Files

Four stimulus files were created in which all possible two-trial combinations of color (red or blue) and stimulus side (right or left) were randomly distributed and presented an equal number of times. For instance, the combination of red-left followed by blue-right – which would not constitute a set of critical stimuli – was presented four times along with all other combinations including critical trials (i.e. red-left followed by red-left). This resulted in a total of 128 trials per stimulus file and allowed for either red or blue to be the target color. Each participant completed two of the four stimulus files with blue serving as the target color in one block and red as the target color in another block. The stimulus file that was used and the order of the target color were counterbalanced across participants.

Results and Discussion (Experiment 3)

The data were analyzed in a 2 X 2 ANCOVA for repeated measures with handedness included as a covariate and reaction time differences between consecutive trials of the same color as the dependent variable. The factors were Color (red or blue) and Hemisphere (left or right). The difference in participants' response times when the same color was presented on consecutive trials was calculated such that negative scores indicate the participant responded faster on trial N than N-1 (i.e. a priming effect was observed), whereas positive scores indicate that the participant was actually slower; specifically: difference = N – (N-1).

As expected, we found a color X hemisphere interaction in which matches (i.e. blue in the RVF/LH and red in the LVF/RH) produced a stronger priming effect than mismatches (i.e. blue in the LVF/RH and red in the RVF/LH), $F(1,28) = 11.72$, $p < .01$. This finding, however, was qualified by a three way interaction that included the handedness covariate $F(1,28) = 9.87$, $p < .01$ (see Appendix C for means). No other effects were significant (color main effect, $F(1,28) = 1.39$, $p > .24$; hemisphere main effect, $F(1,28) = 2.59$, $p > .11$; hemisphere X handedness interaction, $F(1,28) = 2.17$, $p > .15$; all other *F's* < 1). Next, we decomposed the two-way color X hemisphere interaction even though this interaction was found to vary with handedness. We found a stronger priming effect for blue when there was a match versus a mismatch, and priming effects were stronger for red versus blue in the right hemisphere condition, $F(1, 28) = 8.96$, $p < .01$ and $F(1, 28) = 8.74$, $p < .01$, respectively. Thus, we found that priming effects differed depending upon visual field (hemispheric) presentation and electromagnetic frequency level.

That the color X hemisphere interaction was affected by the handedness covariate is not surprising given that use of the right hand primarily activates the left hemisphere and we are attempting to identify an interaction that involves the hemispheres. Moreover, if our predictions are correct, relative left hemisphere activation should have different effects for high versus low frequency colors. That is, as left hemisphere activation increases due to greater amounts of right hand use, this hemisphere should impart a greater amount of influence on participants' behavior. If the left hemisphere is relatively sensitive to high versus low frequency colors then this should increase performance in identifying blue stimuli but may decrease performance in identifying red stimuli. This would result in a difference in the regression slopes for these colors when predicted by handedness and account for the three way interaction. Notwithstanding this result, the findings of Experiment 3 provide the first demonstration that the hemispheres are differentially sensitive to high and low electromagnetic frequency information. If they did not differ, then no difference in priming effects should have been found.

Subsequent analyses

At first glance, it may seem that the color X hemisphere interaction reported in Experiment 3 is driven by a positive priming effect for blue in the right hemisphere condition, compared to relatively equivalent priming effects for blue in the left hemisphere and red in both conditions. Although such a pattern is consistent with some previous work and demonstrates a hemispheric difference in the sensitivity to different frequencies of light, a closer examination of the data provides support for the predicted cross-over interaction (i.e. the one that was observed in the pilot study). In a first analysis, a median split was performed on participants' handedness scores given that the hemisphere X color interaction was found to vary with handedness; Extreme right-handers (N = 16) were defined as those who scored a 100 on the Oldfield handedness inventory (i.e. indicating the greatest possible extent of right hand use) and Moderate right-handers (N = 14) were those who scored relatively lower on this scale (i.e. score = 40-99).

A cross-over hemisphere X color interaction consistent with the current predictions was found for moderate right-handers but there was no reliable pattern for extreme right-handers as a group, $F(1,13) = 5.70$, $p < .04$ and $F < 1$, respectively. For moderate right-handers, we found a significantly stronger priming effect for red versus blue in the right hemisphere condition, $F(1,13) = 4.83$, $p < .05$, and a marginally significant effect for blue between the left and right hemisphere conditions, $F(1, 13) = 2.85$, $p < .12$ (one-tailed, $p < .06$). Even among extreme right-handers, however, the majority of participants (i.e. 11 out of 16) produced a pattern of results inline with our predictions – arbitrarily removing four participants whose pattern of responses was the reverse of that predicted, and one additional participant, revealed the predicted cross-over interaction, $F(1, 10) = 5.85$, $p < .04$. Although there was no a-priori reason to remove these individuals and such results must be interpreted with caution, they suggest that similar findings are likely to be observed for most people (i.e. not just moderate right-handers).

Finally, a similar analysis conducted on the responses of the five participants removed from the extreme right-handers group also produced a significant hemisphere X color interaction, but the pattern of means was the reverse of that predicted, $F(1, 4) = 45.82$, $p < .01$; follow-up contrasts revealed an advantage for red in the left versus right hemisphere and an advantage for red versus blue in the left hemisphere, $F(1, 4) = 10.36$, $p < .04$ and $F(1, 4) = 11.82$, $p < .03$, respectively. The reasons for these discrepancies are unclear, however, and future research will be needed to determine the reliability of these findings. Nevertheless, the results of Experiment 3 provide strong evidence that the hemispheres differ in their sensitivity to different frequencies of light.

Mean (and median) reaction time analyses

Analyses conducted on both mean and median response times failed to reveal any consistent pattern of findings between colors, hemispheres or between participants. Only the hand of response proved to be a clear and significant factor with faster reaction times found when there was a match (left-right and right-left) between hand and hemisphere versus a mismatch (left-left and right-right). We speculate that the reason for this null result is that the identification of different colors occurs multiple times a day and may, therefore, be at or near detection levels as a behavior. If so, we would not expect to find differences consistent with DFF theory; identification but not detection tasks have consistently revealed performance differences between the hemispheres inline with DFF theory predictions (e.g., Kitterle, Christman & Hellige, 1990). Identification tasks require participants to form a judgment about a stimulus ("thin" or "wide" bars, or "high" or "low" auditory frequency) whereas detection tasks require only that the presence or absence of a stimulus is detected. In previous work on visual spatial and auditory frequencies that varied the size of bars or the level of auditory frequencies, the stimuli had to be presented to participants prior to data collection so that they would know what "wide" or "high" meant in the experimental context. This was not the case in this study as participants identified exemplars of primary colors. Therefore, a relatively greater amount of judgment was required to identify stimuli in previous work than in this experiment and this is may have increased the likelihood of observing effects consistent with DFF theory. This notion is consistent with previous work which has found that hemispheric advantages, in general, tend to be greater when task difficulty is relatively high (e.g., Martin, 1979).

Moreover, the fact that our results were observed with a measure of priming and not mean or median response times may indicate that priming magnitude is a relatively more sensitive measure of hemispheric differences. Consistent with this notion, there was no meaningful difference in priming effects when participants used their left or right hand but the hand of response was the only factor that predicted average reaction times. The reason for this is that when priming effects are calculated and the reaction time for trial N is subtracted from trial N-1, all of the person level variables that influence performance, including the hand of response, are eliminated from the equation. This results in a dependent measure that is largely free from such influences and may, therefore, be relatively more sensitive to hemispheric differences than measures of average (or median) reaction times. Future work will be required, however, to determine the accuracy of this account.

In sum, the results of Experiment 3 support the current view and provide independent support for the findings of the first two experiments. Importantly, this study provides the first direct demonstration that the hemispheres are differentially sensitivity to different electromagnetic frequencies. If the hemispheres did not differ in this regard, then no difference in priming should have been found between colors or between hemispheres.

One question that remains, however, is whether this effect occurs on an absolute frequency basis only – as we found – or whether similar effects would be found in terms of relative frequency. That is, frequency levels (i.e. high or low) are not determined by their absolute position on a scale alone but also whether they are relatively higher or lower than the other frequencies that are present in a given context. Moreover, according to DFF theory, hemispheric asymmetries for visual spatial and auditory stimuli are primarily based on relative frequency differences. In addition, prior work has shown that at least for visual spatial frequencies, the hemispheres are differentially sensitive to both absolute and relative frequency levels (e.g., Christman, Kitterle, & Hellige, 1991). Thus, if our proposed extension of DFF theory to include electromagnetic frequencies is correct, we should also find evidence for hemispheric differences in terms of relative frequency. This prediction was tested in Experiment 4.

CHAPTER X

EXPERIMENT 4

The theoretical account upon which our work is based – Double Filtering by Frequency (DFF) theory – proposes that hemispheric differences for visual spatial and auditory frequencies primarily operate on a relative frequency basis (e.g., Ivry & Robertson, 1998). Therefore, if our extension of DFF theory to include electromagnetic frequencies is correct, then similar results should be found for high and low frequency colors. To test this prediction, we used a method similar to that used in previous work with visual spatial and auditory stimuli. As reviewed earlier, Christman et al. (1991) varied the relative frequency level of a visual spatial stimulus (e.g., a 2cpd grating) and found that this eliminated a LVF/RH advantage in response time that was observed in a low frequency baseline condition (e.g., .5cpd and 1cpd gratings), but the reverse occurred when the 2cpd stimulus was added to a high frequency context (e.g., 4cpd and 8cpd gratings) – a marginally significant RVF/LH advantage found in the baseline condition was reversed by the 2cpd stimulus and a LVF/RH advantage was found. Thus, the 2cpd stimulus was processed differently based on whether it was relatively higher or lower than the other visual spatial frequencies in the context.

Experiment 4 also compared baseline performance to relatively high and low frequency conditions. In this study, however, the baseline condition was one in which participants identified whether a stimulus was green or gray and no background color was presented. The relatively high and low frequency conditions consisted of the same stimuli presented over a red or blue background, respectively. If hemispheric differences in color perception are primarily based on relative frequency differences then a RH versus LH advantage should be found in the relatively low frequency condition (i.e. when the background color is blue) but the opposite pattern should be observed in the relatively high frequency condition (i.e. when the background is red). Essentially, the reverse of these results should be found if hemispheric differences are primarily based on absolute frequency differences; as the red background will create an overall lower frequency context, a RH versus LH performance advantage should be found, but when blue is the background an overall higher frequency context will be created and a LH versus RH advantage should be found. This difference in the expected pattern of results allows for a determination of whether hemispheric differences in color perception are primarily relative or absolute in nature.

Little or no difference is expected between hemispheres in the baseline condition as green is near the middle of the visual spectrum and gray is a balanced composite of frequency levels. If any difference is observed, a slight RH advantage is expected due to this hemisphere's superior ability on visual search tasks (see Poynter & Roberts, 2012 for review).

Method (Experiment 4)

Participants and Design

Thirty one right-handed female undergraduates participated in Experiment 4; one was removed prior to data analysis, however, because their responses to the handedness questionnaire indicated that they were not right handed (i.e. score < 40). Three others were eliminated due to missing values in their data. Thus, responses for 27 participants were included in the analysis. All reported normal or corrected to normal vision and indicated that they were not color blind. Visual field presentation (left or right), stimulus color (gray or green) and relative frequency level condition (baseline, relatively high or relatively low) were varied in a 2 X 2 X 3 repeated measures design. Each frequency level condition consisted of a block of 128 trials in which the participant's task was to identify whether a stimulus was green or gray.

Stimuli

Stimuli consisted of a green or gray rectangle 2" X 4" in size similar to the ones used in Experiment 3. The green stimulus had RGB values of 0,194,0, and the gray stimulus had RGB values of 194,194,194. When present, the blue or red background was 3" X 6" and had RGB values of 0,0,194, or 194,0,0, respectively; the green (or gray) target stimulus was centered horizontally on the inner edge. Saturation and brightness were balanced for all colors.

Procedure

Data was collected from each participant individually and handedness was assessed prior to each session using the Edinburgh handedness inventory (e.g., Oldfield, 1971); a score of 40 or greater indicated right handedness. The rest of the procedure was similar to that used in Experiment 3 with the exception that participants completed the same task in all conditions – they identified whether the stimulus presented was green or gray. These stimuli appeared by themselves in the no background baseline condition, over a red background in the relatively high frequency condition and over a blue background in the relatively low frequency condition. Participants completed one block of 128 trials for each of the three frequency level conditions. As in Experiment 3, the side of stimulus presentation was determined by a counterbalanced stimulus file to ensure that an equal number of critical trials were presented in each condition. The hand of response (i.e. left or right), the order in which the blocks were presented and the stimulus file that was used in each condition were also counterbalanced across subjects.

Analysis Plan

Initial analyses will examine priming effects and consist of an ANCOVA in which the full repeated measures model will be entered along with two covariates – participant's degree of right handedness and their overall error rate. Error rate was not controlled for in Experiment 3 because the program that was used in that experiment did not track error rate precisely for each participant. After analyzing the full model, the baseline condition will be removed to focus on the relatively high and low frequency conditions; differences in priming between these conditions provide the critical test of whether hemispheric differences in color perception are primarily based on relative or absolute frequency levels. Although no differences are expected between the green and gray rectangle conditions, if any possible differences are detected, additional analyses will also be conducted for each color separately. Moreover, given that the various predictions for absolute versus relative frequency differences allow for specific expectations about the direction in which effects should occur, one-tailed p-values will be included when reporting the results of any contrasts based on a significant interaction.

Any higher level interactions that include a covariate will also be investigated as in Experiment 3, and differences in mean reaction times will be analyzed.

Results and Discussion (Experiment 4)

In an initial test of priming effects, a 2 X 2 X 3 ANCOVA for repeated measures was conducted with reaction time differences between consecutive trials of the same color as the dependent variable. The factors were Visual Field (left or right), Color (green or gray) and Frequency Level Condition (baseline, relatively high or relatively low). The difference in participants' response times when the same color was presented on consecutive trials was calculated as before (i.e. difference = N – (N-1)). Participant's degree of right handedness and their error rate were controlled for by including these variables as covariates.

This analysis revealed a non-significant Color X Frequency Condition interaction that was qualified by significant interactions with handedness and participant's error rate, $F(2,23) = 2.72$, $p < .09$, $F(2,23) = 4.25$, $p < .03$ and $F(2,23) = 3.53$, $p < .05$, respectively. Although the two-way interaction was not significant, it was nevertheless indicative of some difference in the pattern of priming effects for each color; separate analyses are, therefore, presented for each color below. More central to the current investigation, a non-significant Visual Field X Frequency Condition interaction was also observed, $F(2,23) = 2.16$, $p < .14$ (see Appendix D for means). Though this interaction was not significant, the overall pattern of priming effects was roughly inline with an absolute frequency account and performance in the baseline condition was descriptively intermediate to that in the relatively high and relatively low conditions. No other effects were significant (Visual Field X Frequency Condition X error rate interaction, $F(2,23) = 2.40$, $p > .11$; Visual Field X Frequency Condition X Color interaction, $F(2,23) = 2.10$, $p > .14$; Visual Field X Frequency Condition X Color X error rate interaction, $F(2,23) = 2.06$, $p > .14$; Color X Visual Field interaction, $F(1,24) = 1.19$, $p > .28$; Color X Visual Field X error rate interaction, $F(1,24) = 1.36$, $p > .25$; all other *F's* < 1).

Next, we removed the baseline condition from the analysis to focus more specifically on the interaction between Visual Field and Frequency Condition. This resulted in a 2 (Visual Field: left or right) X 2 (Color: green or gray) X 2 (Frequency Condition: relatively high or relatively low) repeated measures analysis that controlled for handedness and participant's error rate. As before, a three way interaction between Color, Frequency Condition and the handedness covariate was observed, although the two way interaction between Color and Frequency Condition was not significant, $F(1,24) = 8.80$, $p < .01$ and $F(1,24) = 1.14$, $p > .29$, respectively. A Visual Field X Frequency Condition interaction similar to that observed in Experiment 3 was also found, although this was qualified by a three way interaction that included the error rate covariate, $F(1,24) = 4.48$, $p < .05$ and $F(1,24) = 5.00$, $p < .04$, respectively. Notwithstanding, contrasts conducted on the Visual Field X Frequency Condition interaction revealed that – consistent with an absolute frequency account – priming effects were significantly greater for the blue versus red background in the LH presentation condition, and there was a marginal difference in priming between hemispheres when the background was blue (i.e. LH > RH), $F(1,24) = 4.97$, $p < .04$ and $F(1,24) = 3.23$, $p < .09$ (one-tailed, $p < .05$), respectively.[2] No other effects were significant (Color main effect, $F(1,24) = 1.24$, $p >$

.27; Color X error rate interaction, $F(1,24) = 1.22$, $p > .28$; Color X Frequency Condition X error rate interaction, $F(1,24) = 2.42$, $p > .13$; Visual Field X Frequency Condition X Color interaction, $F(1,24) = 2.34$, $p > .13$; Visual Field X Frequency Condition X Color X error rate interaction, $F(1,24) = 2.34$, $p > .13$; all other *F's* < 1).

Subsequent Analyses

To investigate possible differences in the pattern of priming effects for each color, separate 2 (Visual Field: left or right) X 3 (Frequency Condition: baseline, relatively high or relatively low) repeated measures analyses were conducted for the gray and green rectangles. A Visual Field X Frequency Condition interaction was found when the analysis was restricted to gray but not when it was restricted to green, $F(2,23) = 4.01$, $p < .04$ and $F < 1$, respectively. A similar pattern was observed when the baseline condition was removed from the analysis – the Visual Field X Frequency Condition interaction was significant for the gray but not the green rectangle, $F(1,24) = 6.67$, $p < .02$ and $F < 1$. Follow-up contrasts conducted on the gray rectangle based interaction revealed that priming effects were greater in the RH when the red versus blue background was present, they were marginally greater in the LH for blue versus red, and marginally greater between the left and right hemispheres when there was a match versus a mismatch, $F(1,24) = 6.03$, $p < .03$, $F(1,24) = 3.72$, $p < .07$ (one-tailed, $p < .04$), $F(1,24) = 3.27$, $p < .09$ (one-tailed, $p < .05$) and $F(1,24) = 4.09$, $p < .06$ (one-tailed, $p < .03$), respectively.[2] Although descriptive support was observed for the green stimulus, no contrasts were conducted given the lack of a significant interaction. Thus, more support for the current view was observed when participants identified the gray versus green rectangle.

According to our account, however, little or no difference should have been observed between colors because, in terms of frequency, both are near the middle of the visual spectrum. So why was a difference found? One possibility is that gray and green are processed differently at the sensory level and this has consequences for later processes that form judgments and decisions. Although DFF theory proposes that sensory level processes should not influence the current results, green and gray are processed along different visual pathways, with green being processed along the same pathway as red. Consistent with this notion, somewhat more of a RH bias was observed in the baseline condition for the green than gray rectangle.

Nevertheless, a closer examination of the data revealed that most of the difference arose among participants who also committed relatively more errors; when the analysis was restricted to only those participants who were at least 90% accurate in all conditions, almost no RH bias was found in the baseline condition for the green rectangle (i.e. LH: -.18ms; RH: -6.77ms) but a nearly significant RH advantage for the gray rectangle was found (i.e. LH: -9.74ms; RH: -28.13ms), $F < 1$ and $F(1,17) = 4.24$, $p < .06$, respectively. Both results are inconsistent with the notion that differences in the sensory level processing of green and gray account for performance differences in the current study. Therefore, it is unclear whether sensory level differences or a lack of motivation on the part of some participants accounts for this result. Given the entirety of the results across all studies and previous work on spatial and auditory frequencies, the latter is most likely the case.

Finally, additional analyses that investigated mean reaction times and how participants' degree of right handedness influenced the results failed to produce any meaningful pattern (see Appendix E for mean reaction times). For mean reaction times, an effect for the hand of response was found but there was no difference between colors or hemispheres. For the handedness covariate, a median split resulted in a descriptively similar difference between the moderate and extreme right handers groups as that found in Experiment 3, but the difference was not as great. Although the reasons for this are unclear, it may be due to the fact that a small number of participants in the extreme right-handers group in Experiment 3 (i.e. 5 out of 16) produced a significant reverse pattern and this did not occur in Experiment 4. Certainly, the presence of these individuals in the analysis of Experiment 3 increased the difference found between the moderate and extreme right-hander groups. If so, then there may be less difference between these groups than indicated by the results of Experiment 3, which would imply that the current findings are likely to apply to most people. Notwithstanding, the results of Experiment 4 are consistent with the first three experiments and provide additional evidence that the left and right hemispheres are differentially sensitive to high and low electromagnetic frequencies.

CHAPTER XI

GENERAL DISCUSSION

Although color is one of the most basic and pervasive elements of our visual world, little theory has been developed to explain how different colors might influence behavior. Most of the accounts that have been proposed only make predictions for one or two colors in a given context and offer little help in predicting how a color might influence behavior in another setting. Thus, an extension of DFF theory was proposed and the results of four experiments were reported to (1) investigate hemispheric differences in color perception, with the goal of providing a theoretically based, context independent account, and (2) examine whether these differences are primarily based on relative or absolute frequency levels.

Experiments 1 and 2 provided initial support in terms of absolute frequency differences while ruling out an alternative "match" hypothesis; a known hemispheric effect was conceptually replicated when red and orange backgrounds produced relatively larger attribute framing effects than blue and purple backgrounds. Experiment 3 offered converging evidence by varying visual field presentation and measuring participant's reaction time in identifying high or low frequency stimuli – results that also supported an absolute frequency based account. Finally, Experiment 4 provided a direct test of whether this effect is primarily based on absolute or relative frequency differences. The results of this experiment also supported an absolute frequency account; when participants identified a green or gray stimulus that was either relatively higher or lower in frequency than the background on which it was presented, the pattern of priming effects replicated that of Experiment 3 (see Appendix F for a summary of all four experiments). Thus, an initial demonstration and replication of two considerably different effects not only provided converging evidence for the notion that the hemispheres are differentially sensitive to high or low electromagnetic frequencies, they also suggest that this effect is primarily based on absolute frequency differences. Although only right-handed females took part in Experiments 3 and 4, the current results would also be expected to apply to males and to those without a strong right-hand preference as previous work has found little or no difference in lateralization effects among these individuals (e.g., Hellige, 1990; Tomarken, Davidson, Wheeler, & Doss, 1992).

As noted, however, if our proposed extension of DFF theory is correct, then we should also find differences in terms of relative frequency level. So why didn't we observe these effects in Experiment 4? Perhaps, contrary to the current view, hemispheric differences in color perception are primarily based on absolute frequency differences and an extension of DFF theory is not appropriate. If so, another theory would need to be suggested, although no theory would currently make this prediction. Another possibility is that the participant's task was very easy and required little more than detection level processing. If so, then any relative frequency differences may have been harder to detect; research has shown that lateralization effects tend to be more pronounced when task difficulty is higher (e.g., Martin, 1979). Regardless, Experiment 4 represents the only direct test of a relative frequency account and more tests are needed before any firm conclusions can be drawn.

One possible way to address this issue that should also result in differences in mean reaction times would be to replicate earlier work with visual spatial stimuli (i.e. gray hierarchically structured letters) but include conditions in which high or low frequency background colors are presented. Such a study, because it would include conditions identical to those in which differences in mean reaction times have been found, should also result in differences in mean reaction times, but these would be expected to differ in the conditions that included a background color. As in Experiment 4, it would be possible to detect differences in terms of relative or absolute frequencies – if relative frequency differences are observed, then the RH advantage that is typically found for processing low frequency visual spatial stimuli should be enhanced by the presence of a blue background but it should be diminished when a red background is presented; the opposite of these predictions would support an absolute frequency account.

Notwithstanding, the results of the current experiments provide strong evidence that the hemispheres differ in their sensitivity to different frequencies of light. It is difficult to imagine how these results could have been obtained if there was no difference in this regard. Particularly in Experiments 3 and 4, no difference should have been found between the high and low frequency conditions unless the hemispheres were differentially sensitive to these manipulations. The presence of an interaction between hemisphere and color in both experiments also eliminates a host of alternative interpretations that would result in main effects (i.e. the direction participants were gazing, differences in luminance between colors or between sides of the monitor, that one color is more energizing or threatening than another, etc.). Although alternative accounts may be more likely for Experiments 1 and 2, four colors were used to reduce the likelihood that the results were due to the contextual influence of a given color and the results were consistent with the current view. Thus, whether or not DFF theory will ultimately be shown to accurately account for hemispheric differences in color perception, it seems clear that there are differences in how the hemispheres identify color, with the RH being relatively more sensitive to low frequency colors and the LH more sensitive to high frequency ones. Implications and possible applications of this finding are discussed in the following sections.

CHAPTER XII

PREVIOUS WORK REVISITED

If the current view is correct and the left and right hemispheres are relatively sensitive to high versus low frequency colors, respectively, then reinterpretations of several findings in the area of color psychology are possible. One such finding involves message framing. As described earlier, Gerend & Sias (2009) found a significant message framing effect (loss > gain) when a red but not a gray background was used and the authors attributed this finding to red acting as a threat cue. This result would be expected from an extension of DFF theory, however, without the threat cue assumption. My alternative explanation rests on the finding that the message framing effect is more pronounced when right versus left hemisphere processing is enhanced (McCormick & Seta, 2012). Thus, if – because of their frequencies – red activates right hemisphere processing to a greater extent than gray then the message framing effect should be more pronounced when presented on a red versus gray background.

Another area in which DFF theory may be able to provide some explanation involves the visual search findings of Lindsey et al. (2010). In this work, search times were fastest for warm colors like red and orange but slowest for cool colors like blue and purple. While their model fit their view well, the exact pattern of findings observed in this study would be expected from the current view given that performance seems to have increased with right hemispheric activation due to color frequency and that studies have found that the right hemisphere has an advantage in visual search tasks like this (see Poynter & Roberts, 2011 for review). As electromagnetic frequencies decrease from high (i.e. purple) to low (i.e. red), I would expect that hemispheric activation should shift from the left to right hemisphere and visual search times should increase.

Finally, the current view is also able to provide an explanation for the intellectual performance findings exemplified by Maier, Elliot, & Lichtenfeld (2008) (e.g., Elliot et al., 2007; Lichtenfeld et al., 2009; Maier, Elliot, & Lichtenfeld, 2008; Tanaka & Tokuno, 2011). In this work, lower performance was found on an analytic problem solving task when a red versus gray triangle appeared in the context and it was concluded that unconscious avoidance motivations generated by the red triangle caused this difference. However, an alternative explanation that does not require an unconscious avoidance motivation assumption relies on the finding that analytic tasks, like the one used by these authors, are processed more efficiently in the left versus right hemisphere (e.g., Dehaene et al., 2003; Delazer et al., 2003; Zago et al., 2001). Therefore, if red activates right hemisphere processing to a greater extent than gray then performance on their analytic tasks should have been inferior – as it was – when it was associated with red versus gray. Unfortunately, a blue triangle condition was not included. A blue triangle – because of its frequency – should enhance left hemisphere processing relative to a gray triangle. If so, then the blue triangle would be expected to produce especially good performance scores on an analytic task like the one used by Maier et al. (2008). Such a prediction would not readily follow from the account provided by these authors which is silent on the effect of all colors other than red.

CHAPTER XIII

FUTURE DIRECTIONS

Although speculative, if the current view is found to be correct then one potentially important implication may be that it provides an explanation for the preferred treatment for Seasonal Affective Disorder (SAD) – "light therapy" (e.g., Gagne, Levesque, Gagne, & Hebert, 2011; Terman, 2007; Vandewalle et al., 2010). In this treatment, a "light box" consisting of a full spectrum (i.e. white) light is prescribed to patients who are instructed to sit in front of it for around 30min each day, and morning hours are preferred to later ones. The effectiveness of this treatment has been shown to be on par with the use of antidepressants in reducing SAD related symptoms (e.g., Partonen & Lonnqvist, 1996). Of note, the addition of a small amount of blue light to the full spectrum light normally used has been found to be particularly effective (e.g., Azeemi & Raza, 2005; Gagne et al., 2011; Terman, 2007; Vandewalle et al., 2010).

Unfortunately, however, as the underlying causes of SAD have not been fully elucidated, the underlying causes of the benefits of light therapy also remain unclear (e.g., Flaskerud, 2012; Gagne et al., 2011). It is likely that "phase-shifted circadian rhythms" resulting from changes in the availability of sunlight play some role, but such rhythms are unlikely account for differences in SAD population rates between communities with similar light availability or for how SAD appears to be heritable and to have at least some genetic component (e.g., Flaskerud, 2012). Given this uncertainty surrounding SAD and the use of light therapy, “documented therapeutic efficacy” has been cited as the primary justification for this treatment (e.g., Gagne et al., 2011).

Nevertheless, a theoretically based explanation for the benefits of light therapy may be provided by the current view if the activity levels of the left and right hemispheres of SAD patients are similar to that of patients with non-seasonally related depression. Research has shown that this latter form of depression is associated with a hyperactive right hemisphere and a hypoactive left hemisphere (e.g., Hecht, 2010). If this also holds for SAD patients, then, from the current view, it would be expected that a full spectrum light would aid patients by providing nearly equal activation to both hemispheres, thereby restoring balance to overall activity levels and reducing depressive symptoms. The inclusion of blue light (i.e. a high electromagnetic frequency light) would also be expected to be beneficial as it would provide slightly greater activation to the left versus right hemisphere, possibly providing a respite from long hours of the reverse or a buffering effect for when the day’s treatment is over. Thus, light therapy would primarily be seen as balancing or correcting hemispheric activity levels. If this reasoning is correct, a small amount of purple light would be expected to have similar effects to blue light and predictions and recommendations for exposure to other colors would be possible as well. No such predictions are possible from current accounts of light therapy.

Another implication is that some colors may be more (or less) appropriate to use during academic testing. Research exemplified by Maier, Elliot, & Lichtenfeld (2008) (e.g., Elliot et al., 2007; Lichtenfeld et al., 2009; Maier, Elliot, & Lichtenfeld, 2008; Tanaka & Tokuno, 2011) demonstrates that exposure to red can have a detrimental effect on academic performance. If this is due to relative activation of the RH, as suggested by the current view, then similar results should be found for exposure to orange but exposure to blue or purple may facilitate academic performance. None of these effects may actually be desirable in a testing situation, however, when the goal is to provide a fair environment for all. Therefore, it may be best to test individuals in predominately gray or green contexts, or to have a standard policy for all important exams (i.e. GRE, SAT, etc.).

A simple application derived from the current view is that different colored backgrounds, whether the paper on which stimuli is presented or the sunset behind a product spokesperson, can be used to enhance left or right hemispheric processing. The findings of the current attribute framing studies and those reviewed with message framing all replicate known hemispheric effects and suggest that different colored backgrounds activated different hemispheres. If so, these findings may be applied to billboards, posters, health pamphlets and possibly to online and television based materials. The use of high or low frequency amplification would depend on the specific application but in all cases low electromagnetic frequency amplification would take advantage of the properties of right hemisphere processing, whereas, high frequency amplification would take advantage of left hemisphere processing.

Another possible application relates to persuasion-based attitude change and is based on work by Ley & Bryden (1982). These researchers found that for the same sentences (i.e. messages), participants were better able to remember the content of the message when it was played in the right ear/LH but they were better able to remember the emotional tone of the message when it was played in the left ear/RH. Based on the persuasion literature, it is known that messages are more effective when there is a match between a message and the component of the attitude that it is attempting to change – cognitive, affective or behavioral (see Clarkson, Tormala, & Rucker, 2007 for review). When buying a car or refrigerator, for instance, individuals tend to form a cognitively based attitude and a message that changes a person's cognitions will be more effective than one that tries to change how a person feels about the product. Thus, advertisers of these products try to increase the likelihood that individuals will remember the content of their message and one way to do this may be to enhance LH processing by incorporating high frequency colors in the decision context. For many other products, however, such as food, clothing and other fashion items, individuals are more likely to form an affective based attitude. In these cases, advertisers want individuals to be more sensitive to the tone or feeling of the message and one way to do this may be to enhance RH processing using low frequency colors.

Numerous other implications and possible applications also exist. For example, it may be possible to help individuals overcome faulty intuitions or reduce consumer's reliance on the types of inferences that lead to suboptimal decisions by using different colored stimuli (e.g., Alba & Hutchinson, 1987; Alter, Oppenheimer, Epley, & Eyre, 2007). In each case, the application would take advantage of one or more of the numerous differences between the hemispheres that have been identified in over 40 years of lateralization research. These possibilities offer exciting opportunities for future research.

CHAPTER XIV

CONCLUSION

The results of four experiments provided support for our proposed extension of DFF theory. In the first two studies, attribute framing effects were pronounced when a red or orange background was used but there was no difference between frames when the background was blue or purple. Experiment 3 added to these findings by varying visual field presentation and providing a more direct demonstration of hemispheric difference in the sensitivity to different colors. A fourth experiment replicated this finding and indicated that the result is primarily based absolute frequency differences. Thus, an initial demonstration and replication of two different findings converged to support the current view that the right hemisphere is more sensitive to low frequency colors whereas the left hemisphere is more sensitive to high frequency colors. It is unclear how these findings would be predicted from any other view.

In addition to this evidence, reinterpretations of several findings in color psychology and related areas supported the current account. In each case, a straightforward reinterpretation was offered based on the electromagnetic frequencies of the various color conditions in that study and empirical work was referenced to support the account. Although each of these interpretations was post-hoc and would require future work to verify, the possibility that a single account can be provided for such a diverse set of findings is desirable in terms of parsimony.

In sum, I believe that an extension of DFF theory to include electromagnetic frequencies is not only possible but that it likely provides an accurate account of at least some of the context independent influence that different colors can have. If so, a parsimonious account can be provided for many previous findings and an important caveat for future work will have been identified – color manipulations are also likely to affect hemispheric activation. This account also affords a number of novel predictions in different areas and could lead to important real world applications.

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FOOTNOTES

1. The results of this experiment must be considered preliminary for several reasons. First, only four participants took part in the study and each was hand selected rather than randomly drawn from the population. Moreover, given a random side of presentation, red did not appear in the LVF(RH) on consecutive trials for one subject; the average RT difference found for the other three subjects was therefore substituted in this cell to allow for a repeated measures analysis on all four participants. Nevertheless, a priming effect based analysis similar to that described in Experiment 3 provided considerable support for the current predictions.
2. Although some contrasts were only significant at the one-tailed level, with a larger sample they might have been significant at the two-tailed level. Nevertheless, given that we predicted the direction in which these effects should occur, one-tailed analyses are appropriate to report.

APPENDIX A

AVERAGE PRODUCT EVALATIONS I

Background Color:	Frequency level:	Valence: Positive N	Positive Mean (SD)	Negative N	Negative Mean (SD)
Red	Low	7	6.50 (1.08)	7	4.86 (1.28)
Orange		6	7.25 (1.33)	4	5.75 (2.40)
		13	6.85 (1.21)	11	5.18 (1.71)
Blue	High	6	6.02 (1.76)	7	6.29 (1.38)
Purple		7	6.02 (1.28)	7	5.93 (1.02)
		13	6.02 (1.45)	14	6.11 (1.18)

- Combined fat/lean and greasy/greaseless product evaluations as a function of valence and background color. Frequency X Frame interaction, $F(1, 47) = 5.08$, $p < .03$; $MSE = 1.92$.

APPENDIX B

AVERAGE PRODUCT EVALATIONS II

		Valence			
		Positive		Negative	
Background Color:	Frequency level:	N	Mean (SD)	N	Mean (SD)
Red	Low	14	7.33 (1.36)	12	5.46 (2.50)
Orange		14	7.11 (1.57)	13	5.65 (2.55)
		28	7.22 (1.45)	25	5.56 (2.48)
Blue	High	14	7.61 (1.59)	15	7.43 (2.11)
Purple		15	7.43 (1.50)	12	7.23 (1.74)
		29	7.52 (1.52)	27	7.34 (1.92)

- Combined impure/pure and no buy/buy product evaluations as a function of valence and background color. Frequency X Frame interaction, $F(1, 105) = 4.32$, $p < .04$; $MSE = 3.47$.

APPENDIX C

AVERAGE PRIMING EFFECTS I

Hemisphere:	Color: Blue		Color: Red	
	N	Mean (SD)	N	Mean (SD)
Left	30	-12.05 (68.52)	30	-12.57 (56.66)
Right	30	14.41 (70.03)	30	-19.44 (59.51)

- Average response time difference as a function of hemisphere and stimulus color in Experiment 3. Hemisphere X Color interaction significant, qualified by a three way interaction with the handedness covariate, $F(1,28) = 11.72$, $p < .01$ and $F(1,28) = 9.87$, $p < .01$, respectively; $MSE = 2811.94$.

APPENDIX D

AVERAGE PRIMING EFFECTS II

Hemisphere:	Baseline		Red Background		Blue Background	
	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)
Left	27	-5.62 (48.06)	27	-7.92 (35.06)	27	-12.26 (30.54)
Right	27	-10.59 (52.46)	27	-21.64 (31.19)	27	-11.40 (40.49)

Background Color Condition

- Average response time difference as a function of hemisphere and background color condition in Experiment 4. A Hemisphere X Background Color interaction was significant when the no background condition was removed from the analysis, qualified by an interaction with participants' error rate, $F(1,24) = 4.48$, $p < .05$ and $F(1,24) = 5.00$, $p < .04$, respectively; $MSE = 2905.00$.

APPENDIX E

EXPERIMENT 4 MEAN REACTION TIMES

Baseline Condition (no background)

Trial N	Trial N-1 Left-Green Mean (SD)	Left-Gray Mean (SD)	Right-Green Mean (SD)	Right-Gray Mean (SD)
Left-Green	370.79 (52.98)	383.37 (65.62)	393.35 (65.01)	360.10 (69.85)
Left-Gray	419.14 (72.42)	397.82 (60.68)	383.59 (66.37)	424.66 (79.40)
Right-Green	381.54 (61.74)	359.70 (67.40)	366.29 (47.97)	385.01 (53.38)
Right-Gray	370.10 (62.60)	398.68 (58.53)	407.59 (76.17)	392.62 (62.53)

Red Background Condition

Trial N	Trial N-1 Left-Green Mean (SD)	Left-Gray Mean (SD)	Right-Green Mean (SD)	Right-Gray Mean (SD)
Left-Green	383.00 (55.80)	401.17 (55.78)	419.71 (86.52)	361.44 (57.18)
Left-Gray	424.05 (62.69)	397.48 (42.11)	388.45 (63.36)	435.10 (69.09)
Right-Green	403.20 (49.53)	370.33 (70.36)	389.43 (58.41)	390.02 (43.01)
Right-Gray	366.80 (61.62)	413.29 (71.35)	418.37 (75.36)	394.65 (62.32)

Blue Background Condition

Trial N	Trial N-1 Left-Green Mean (SD)	Left-Gray Mean (SD)	Right-Green Mean (SD)	Right-Gray Mean (SD)
Left-Green	383.27 (68.09)	404.96 (67.52)	406.46 (55.79)	373.51 (55.69)
Left-Gray	429.06 (74.57)	395.79 (42.52)	379.21 (40.19)	417.86 (59.50)
Right-Green	386.20 (55.45)	364.51 (61.04)	383.15 (44.31)	403.30 (77.85)
Right-Gray	371.78 (55.43)	396.72 (52.89)	399.45 (65.24)	377.11 (65.24)

- Average response time (in milliseconds) for trial N given N-1 as a function of stimulus color, visual field presentation and background frequency condition in Experiment 4. “Left” refers to the LVF”; “Right” refers to the RVF; “Green” refers to the green stimulus; “Gray” refers to the gray stimulus.

APPENDIX F

SUMMARY OF EXPERIMENTS

Experiment 1: Ground beef framed as 85% lean (gain) or 15% fat (loss).

- Pronounced attribute framing effects (i.e. gain > loss) were found when the background was either red or orange (i.e. low frequency), but not when it was blue or purple (i.e. high frequency); frequency X frame interaction, $F(1, 47) = 5.08$, $p < .03$.
- Results were as predicted and supported an absolute frequency account.

Experiment 2: Bottled water framed as 99% pure (gain) or 1% impure (loss).

- Pronounced attribute framing effects were found when the background was either red or orange (i.e. low frequency), but not when it was blue or purple (i.e. high frequency); frequency X frame interaction, $F(1, 105) = 4.32$, $p < .04$.
- Results replicated Experiment 1, ruled out an alternative "match" hypothesis and provided additional support for an absolute frequency account.

Experiment 3: Blue or red stimuli presented to the LVF/RH or RVF/LH.

- Differences in priming effects provided additional support for an absolute frequency account; a Hemisphere X Color interaction was significant qualified by a three way interaction with the handedness covariate, $F(1,28) = 11.72$, $p < .01$ and $F(1,28) = 9.87$, $p < .01$, respectively.
- Priming effects were greater when there was a match (i.e. blue-left; red-right) versus a mismatch (blue-right; red-left) between hemisphere and stimulus color.

Experiment 4: Green or gray stimuli presented to the LVF/RH or RVF/LH with no background, over a red background, or over a blue background.

- Allowed an examination of whether the effect is primarily based on relative or absolute frequency levels.
- When the no background condition was removed from the analysis, differences in priming effects replicated Experiment 3; a Hemisphere X Color interaction was significant, qualified by an interaction with participants' error rate, $F(1,24) = 4.48$, $p < .05$ and $F(1,24) = 5.00$, $p < .04$, respectively.
- Thus, support for an absolute frequency account was found across four experiments using two considerably different measures.